FCC-Week

Amsterdam - April 10th, 2018

Massimiliano Antonello

on behalf of the **RD_FA INFN Collaboration**

INFN Sez. Milano

Università degli Studi dell'Insubria

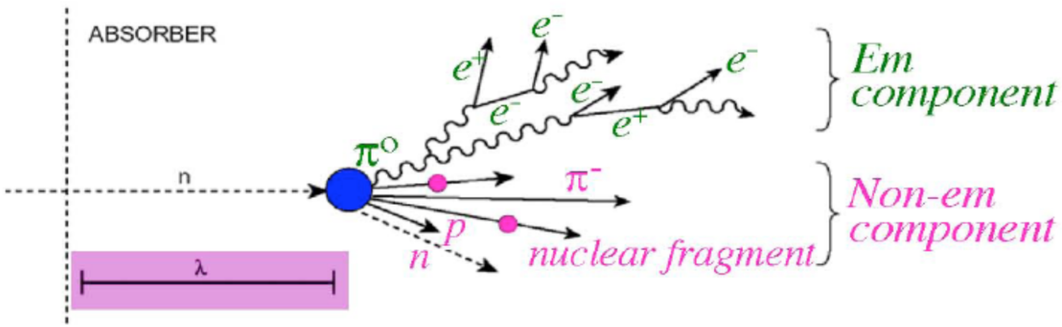
IDEA
Dual-Readout Calorimeter

Hadron showers development

References:
NIM A 537 (2004)

- The hadronic showers are made of two components:
  - **Electromagnetic component:**
    - from neutral meson (π^0, η) decays
  - **Non electromagnetic component:**
    - charge hadrons $\pi^{\pm}$, $K^{\pm}$ (20%)
    - nuclear fragments, p (25%)
    - n, soft γ's (15%)
    - break-up of nuclei (invisible energy) (40%)

[average values in **lead**]



- The main **fluctuations** in the event-to-event calorimeter response are due to:
  - Large non-gaussian fluctuations in energy sharing em/non-em
  - Large, non-gaussian fluctuations in "invisible" energy losses
  - Increase of em component with energy

- The calorimetric performance at collider experiments has always been spoiled by the **problem of non-compensation**, arising from the dual nature of hadronic showers

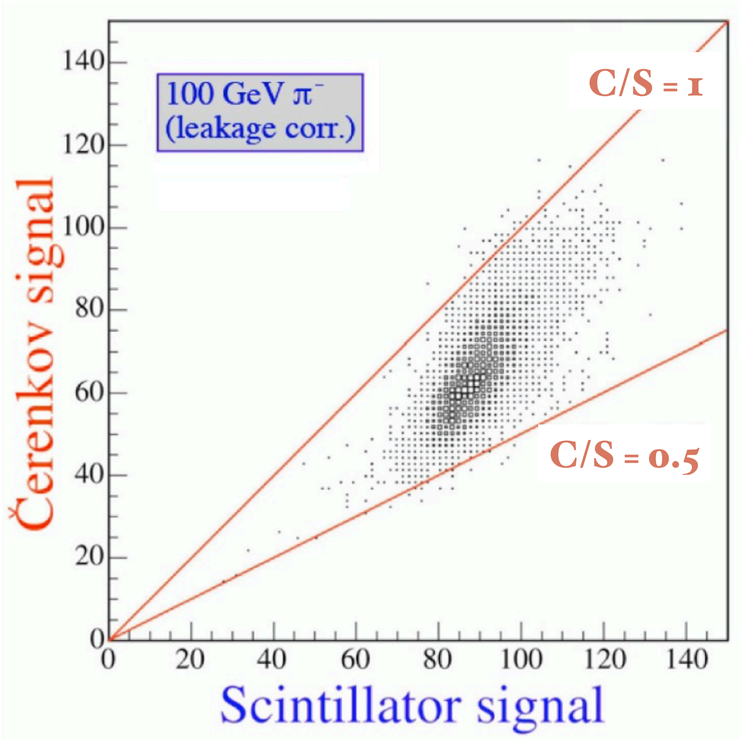
- The **Dual-Readout** calorimetry aims at **solving** this problem by measuring, event by event, the relative fraction of the em and non-em components

Dual-Readout Calorimetry

References:
NIM A 617 129-133 (2010)

- The **Dual-readout** concept: do not spoil em resolution to get **e/h=1** but **measure f_{em}** event by event → eliminate effects of fluctuations in f_{em} on calorimeter performance

- Use 2 different sampling processes: **Cherenkov light** (produced by relativistic particles and dominated by the e.m. shower component) and **scintillation light production** (for the total deposited energy):



$$C = E\left[f_{em} + \frac{1}{(e/h)_C}(1 - f_{em}) \right]$$

$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em}) \right]$$

e.g. if: (e/h) = **1.3(S)** vs **4.7(C)**

$$\frac{C}{S} = \frac{f_{em} + 0.21(1 - f_{em})}{f_{em} + 0.77(1 - f_{em})}$$

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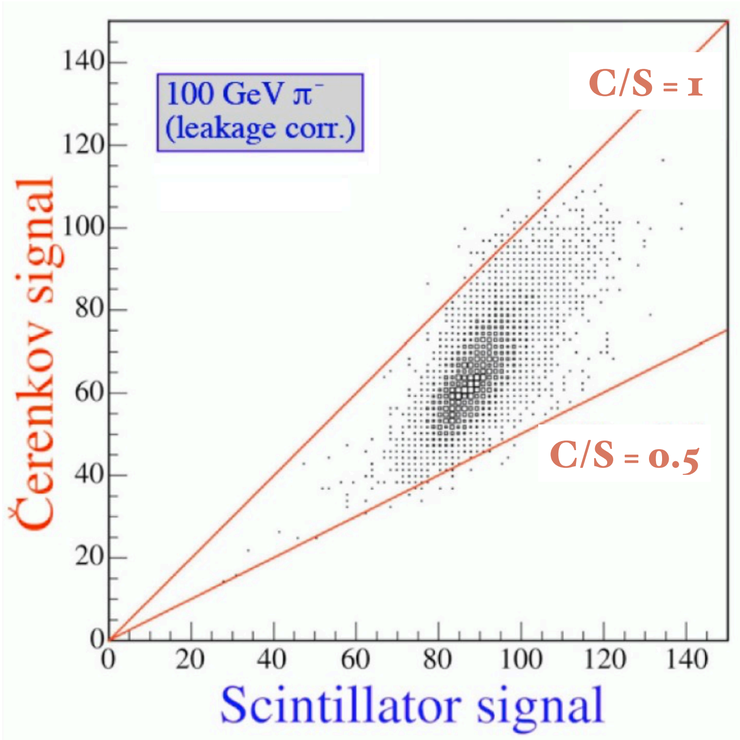

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$$\frac{C}{S} = \frac{f_{em} + 0.21(1-f_{em})}{f_{em} + 0.77(1-f_{em})}$$

$$E = \frac{S - \chi C}{1-\chi}$$

Universally valid!

with: $$\chi = \frac{1-(h/e)_S}{1-(h/e)_C}$$

χ is independent of both:

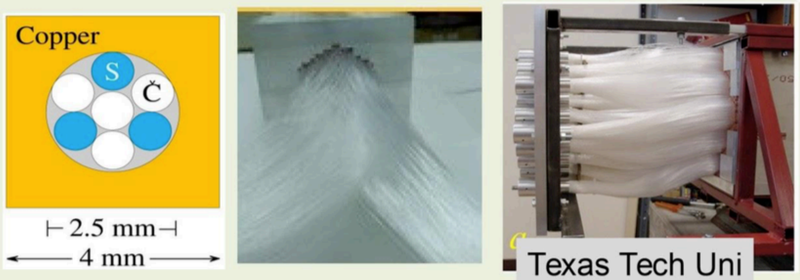
- Energy
- Type of hadron

Dual-Readout Fiber-Sampling Calorimeters

- In the past 20 years the DREAM/RD52 built and tested different prototypes that confirmed the feasibility of this calorimetric technique

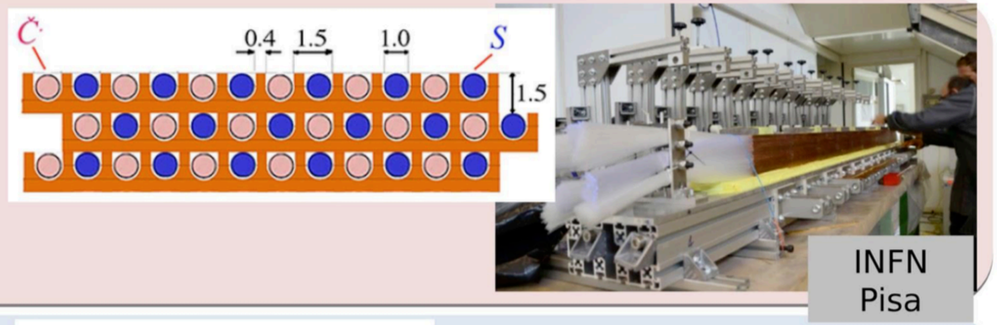
2003 DREAM

Copper
2m long, 16.2 cm wide
19 towers, 2 PMT each
Sampling fraction: 2%



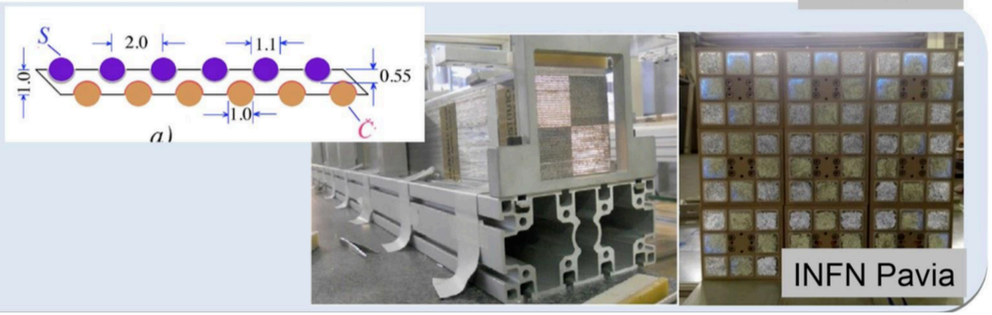
2012 RD52 Copper, 2 modules

Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 4.5%, 10 λ_{int}



2012 RD52 Lead, 9 modules

Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 5%, 10 λ_{int}



Some DREAM/RD52 results

References:

a) NIM A735, 130-144 (2014)
b) NIM A537, 537-561 (2014)
c) NIM A735, 120 (2014)

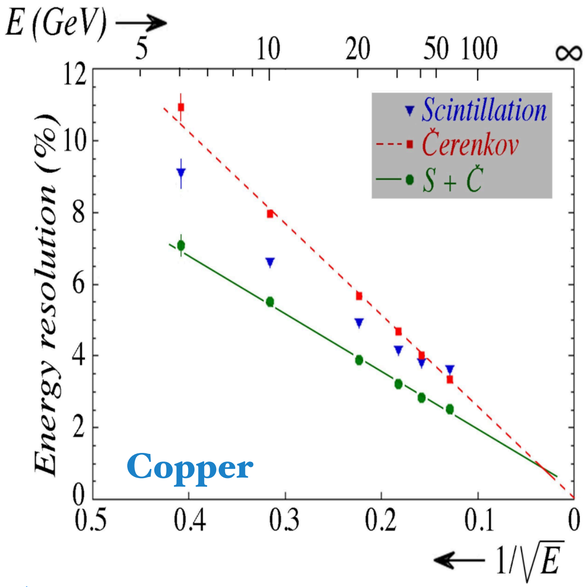
Latest energy resolution performance:

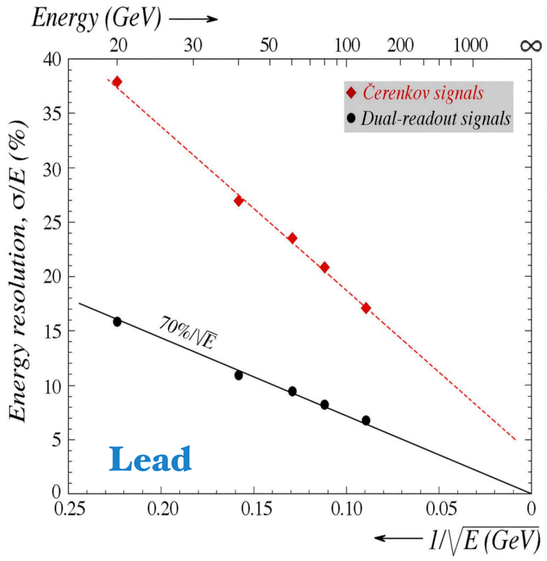
EM RESOLUTION:

Copper module:	Simulated:
$\frac{11\%}{\sqrt{E}} + 1\%$	$\frac{10.3\%}{\sqrt{E}} + 0.3\%$

HAD RESOLUTION:

Lead module:	Simulated:
Lateral Leakage $\frac{70\%}{\sqrt{E}}$	$\frac{34\%}{\sqrt{E}}$





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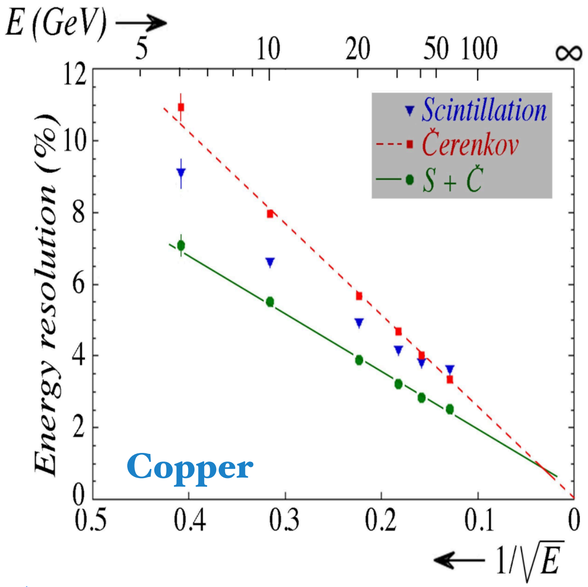
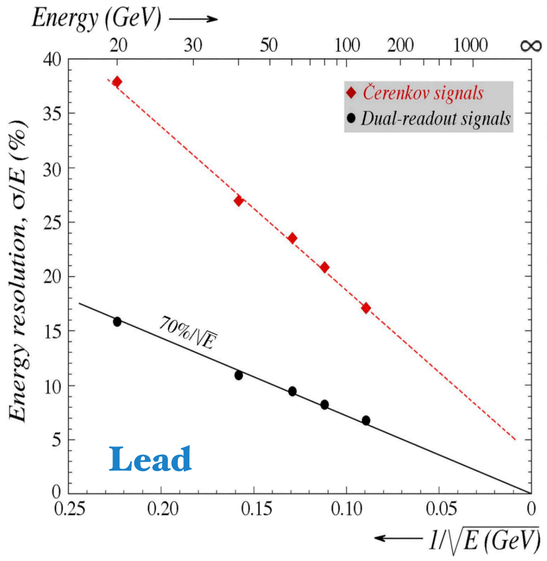




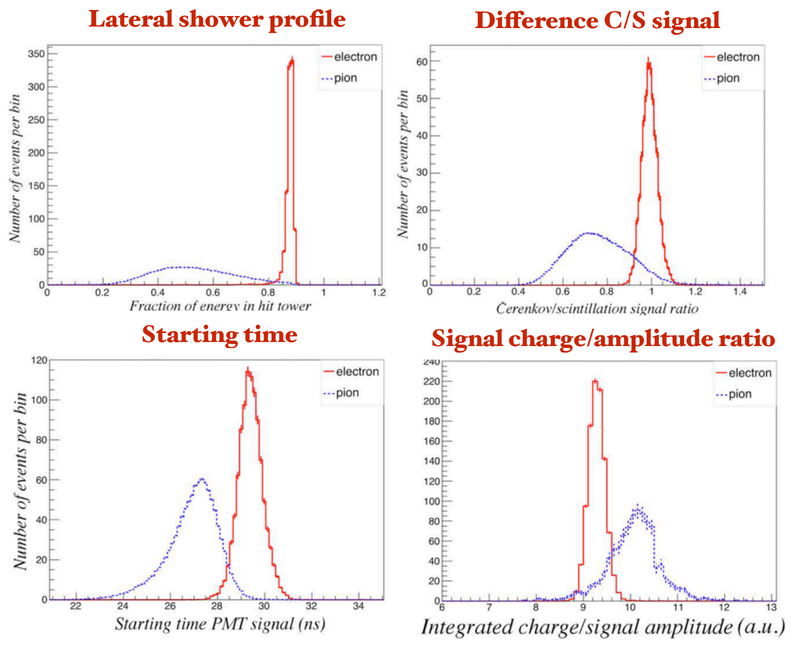
Particle ID (hadron/electron separation):

RD52 lead calorimeter: (60 GeV) e-/π-

- Lateral shower profile
- Difference C/S signal
- Starting time of PMT signals
- Signal charge/amplitude ratio

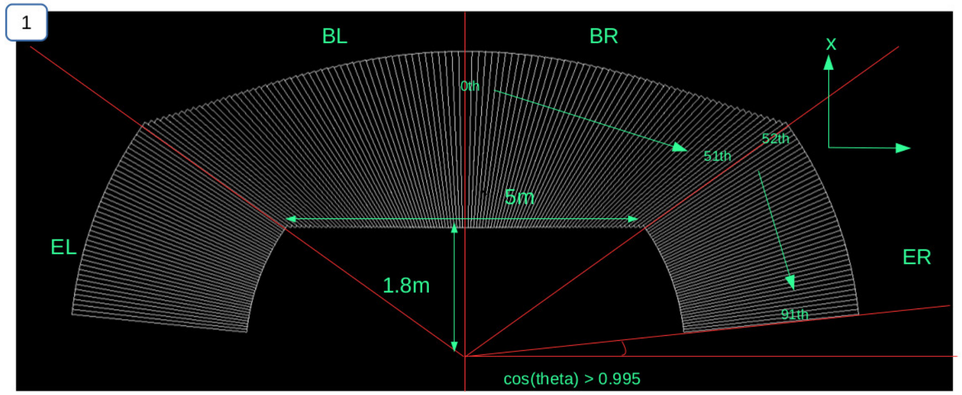
A multivariate analysis reached a particle ID capability of:

ε(e-) = 99.8%
@ R(π-) ~ 500



4π simulations

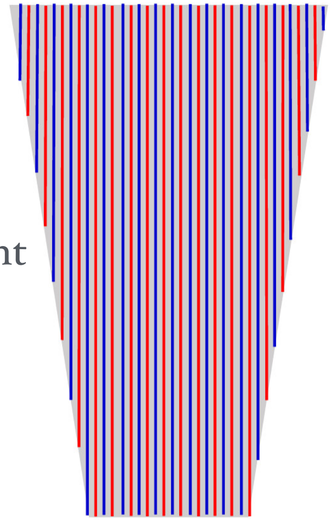
Projective layout: "wedge" geometry

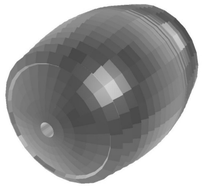


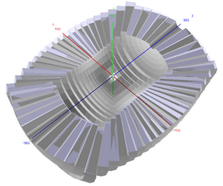
It covers the full volume up to |cos(θ)| = 0.995, with **92** different types of towers (wedge)

A typical one in the barrel:

- **Δθ x Δϕ = 1.27° x 1.27°**
- length of 250 cm (~ 10 λ)
- about **4000 fibres** (starting @ different depths to keep constant the sampling fraction)



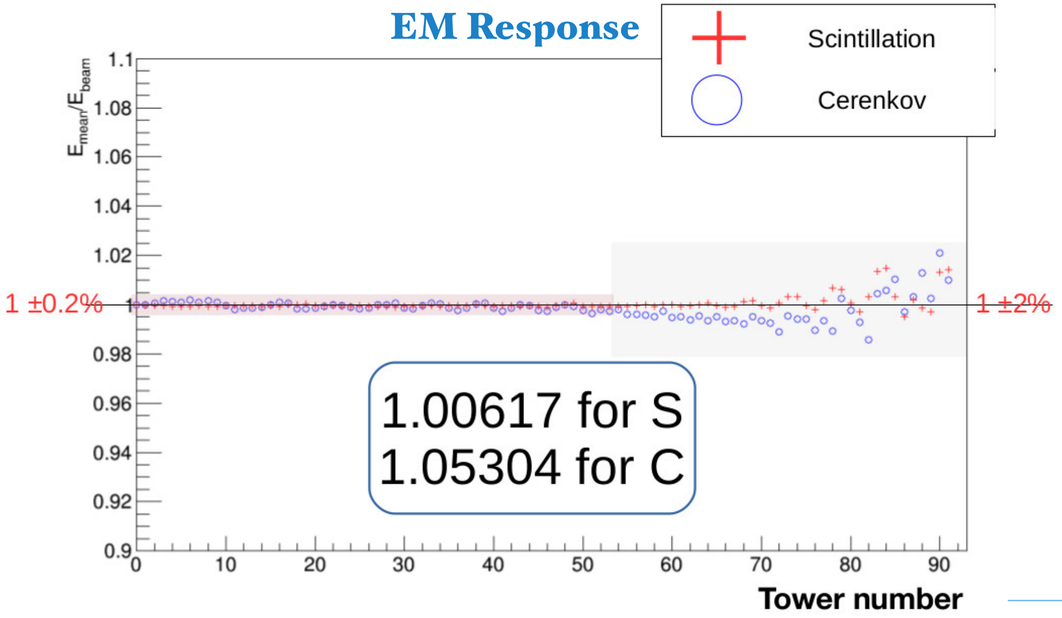




PRELIMINARY RESULTS (to be validated)

- Each tower calibrated to **20 GeV e-**
- Incident angle of (1°, 1.5°)
- Tower response: E_{mean}/E_{beam}
- L.Y. for C channel ~ 30 pe/GeV (as in RD52)

Tower response:
Barrel region: within 0.2%
Endcap region: within 2%



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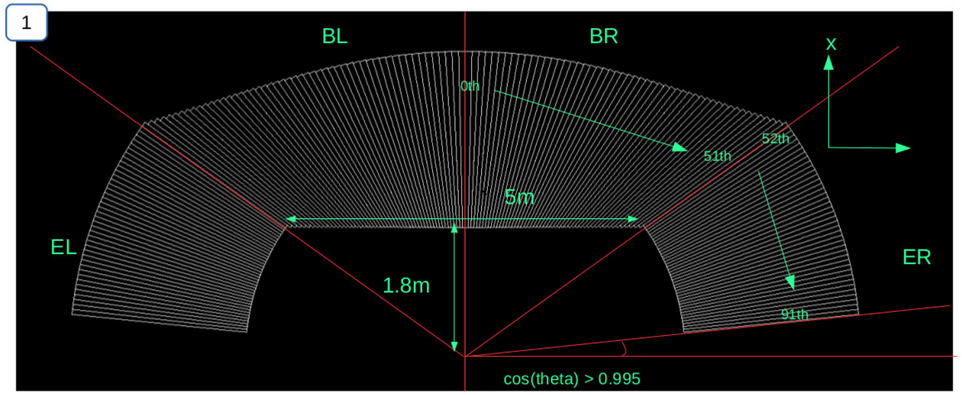

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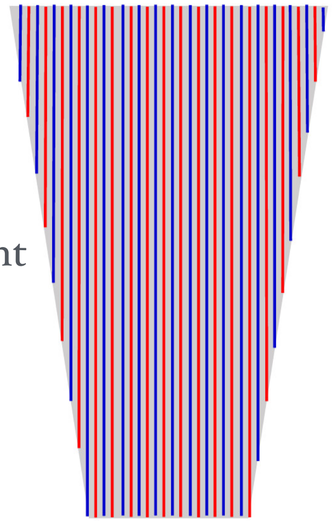
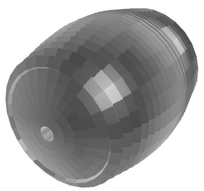
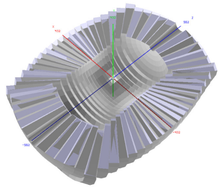






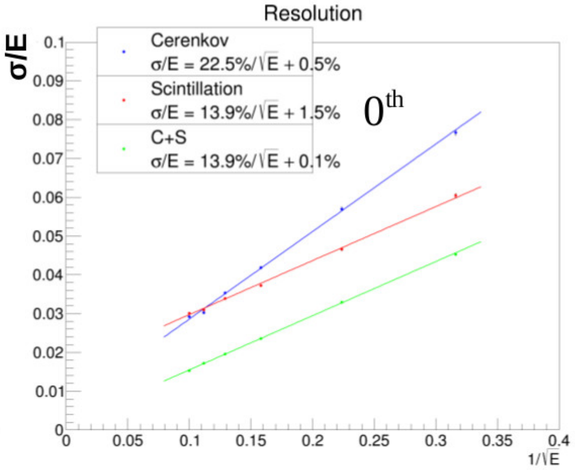
PRELIMINARY RESULTS (to be validated)

In the barrel region:

EM RESOLUTION:

e⁻ from **10** to **100 GeV**
Average response:
100.0 ± 0.4 (%)

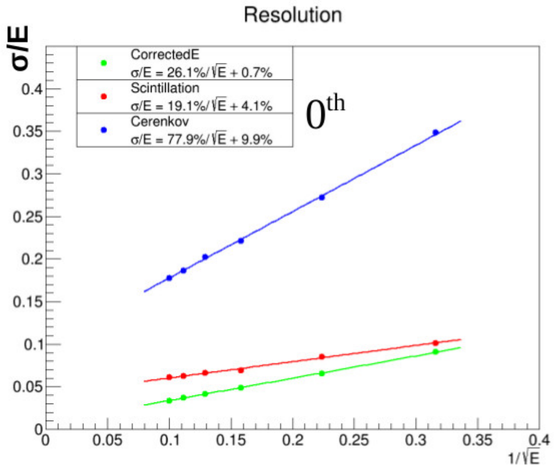
$$\frac{\sigma}{E} \sim \frac{14\%}{\sqrt{E}} + 0.1\%$$



HAD RESOLUTION:

π⁻ from **10** to **100 GeV**
χ = **0.29** (from DREAM)
Average response:
92 ± 1 (%)

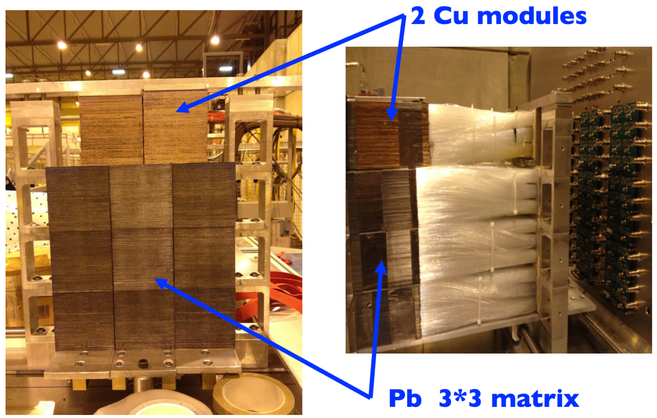
$$\frac{\sigma}{E} \sim \frac{26\%}{\sqrt{E}} + 1\%$$



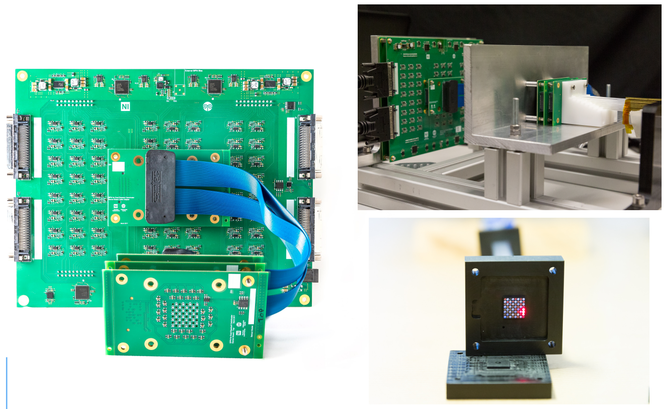
The hadronic energy resolution and the response to single hadrons should be appropriate.

PMT vs SiPM readout

How to fit such a geometry in a collider experiment?



Using a SiPM readout



Advantages

- **Compact readout:**
  - no fibres sticking out (antennas)
- **Possible longitudinal segmentation**
- **Operation in a magnetic field**
- **Higher photon detection efficiency (PDE):**
  - Cherenkov photoelectrons are the limiting factor to the hadronic calorimeter resolution

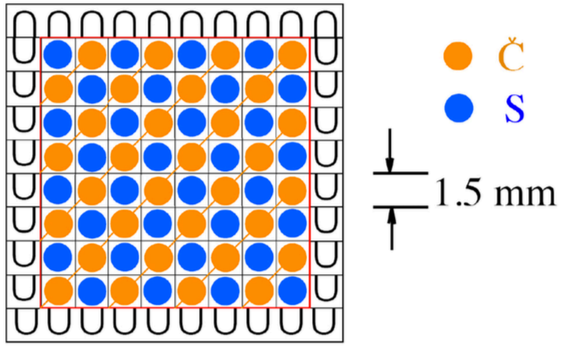
(Potential) Disadvantages

- **Signal saturation**
- **Optical crosstalk between Cherenkov and scintillating signals**
- **Dynamic range**
- **Some instrumental effects:**
  - Temperature gain variation, dark count rate, etc.

2017 test beam layout/selection

*Scintillating fibres: Kuraray SCSF-78
Cherenkov fibres: Mitsubishi SK40

- A 112 cm long, 15 x 15 mm² wide, module was built from stacked **brass** layers, housing 1 mm diameter clear & scintillating fibres* with a **pitch of 1.5 mm** ~ 112 cm long, 15 x 15 mm²



- **X_0 = 29 mm, R_M = 31 mm**
- The calorimeter is **39 X_0** deep and has an effective radius of **0.22 RM**
- According to GEANT4 simulations the em shower **containment** is **45% (S)** and **36% (C)**

Different beam energy and type:
e- beams @ 6, 10, 20, 30, 40, 50, 60, 80, 100, 125 GeV
μ beams @ 50, 60, 125 GeV

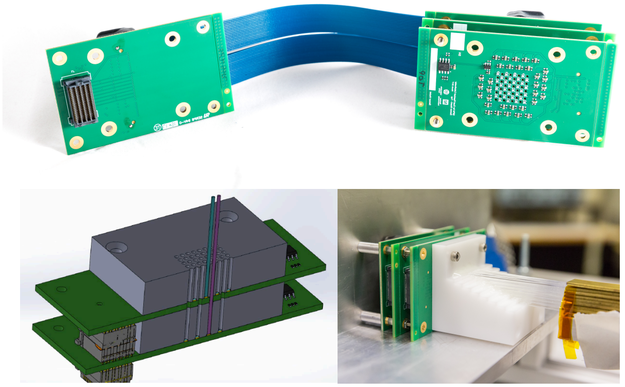
- **Delay Wire Chamber**: selects events in central region
- Trigger: $(T_1.T_2.\overline{T_H})$
- **Preshower** detector: identifies e-
- **Muon** counter: identifies μ

2017 test beam SiPM-based readout

SiPM

HAMAMATSU S13615-1025	
Sensitive area	1×1 mm^2
Cell pitch	25 μm
No. of pixels	1584
Peak Photon Detection Efficiency	25%
Breakdown voltage V_{br}	53 V
Recommended operational voltage V_{op}	V_{br} + 5V
Gain at V_{op}	7×10^5
Dark Count Rate at V_{op}	50 kps
Optical Crosstalk at V_{op}	1%

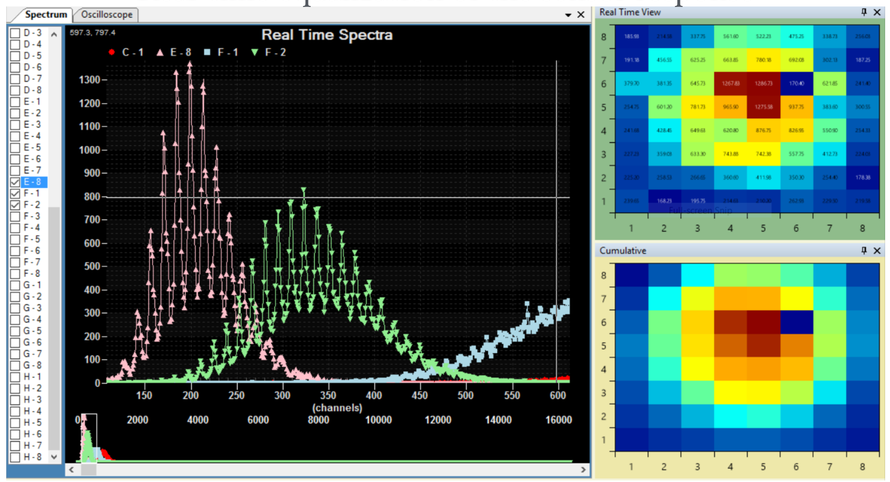
Two different layers: C upstream, S downstream



MADA: Multichannel Analog to Digital Acquisition system

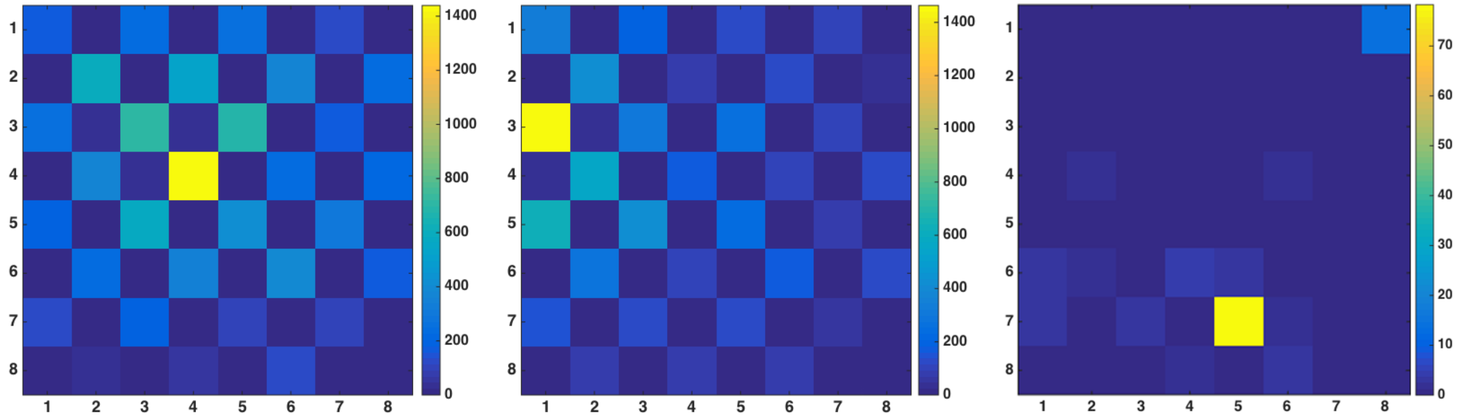
- 32 channel digitizer
- sampling rate **80MSpS/14-bit ADC**
- FPGA-based: real-time charge integration

Real-time equalization of the sensor response



Event display examples

a) *Centered* **10 GeV e- beam** b) *Off-centered* **A muon event**

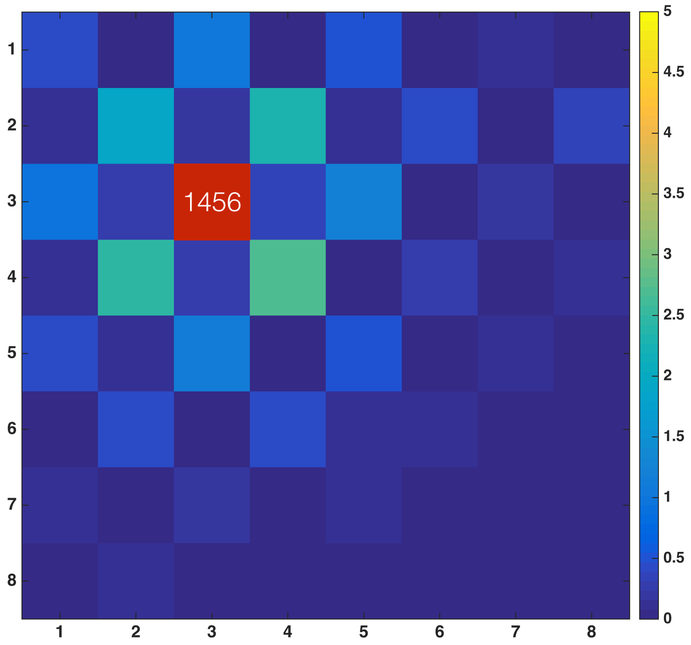


Results: optical crosstalk

- Since the two types of fibres are **located very close** to each other and carry light signals that differ by more than **an order of magnitude** in intensity, the **optical crosstalk** between the signals is a major challenge

- Direct measurement:
  - Only one uncovered S fibre illuminated (**1456** fired cells)
  - The sum of all 32 C signals recorded
  - The matrix shows the **mean number of fired cells** read out by each SiPM

z max truncated to 5 fired cells



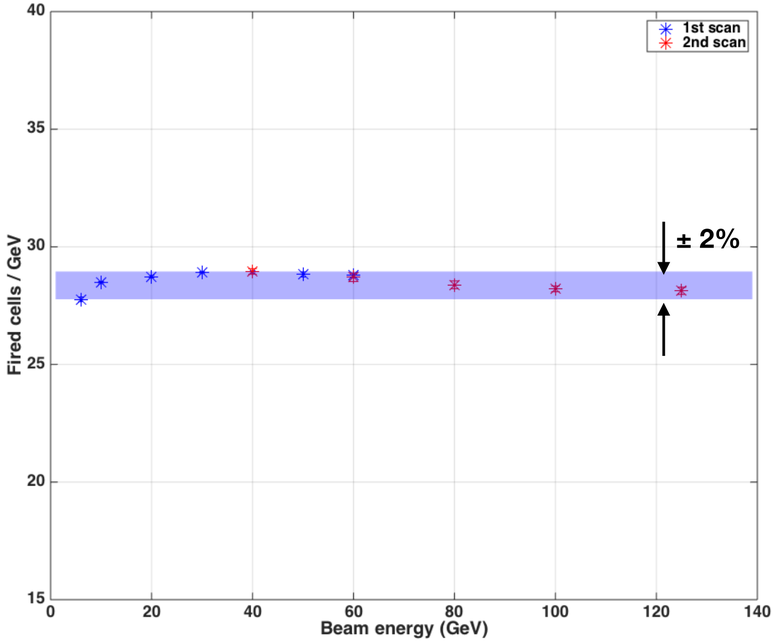
Optical crosstalk
reduced from 25% to
0.3% of the S signal
16% of the C signal

Results: light yield

Cherenkov signal

- V_{op} = **5.5 V_{ov}** (57.5 V)
- A mean number of ~ **28.4 fired cells/GeV**
- Correcting for the containment (36%) **69 ± 5 fired cells/GeV**

LY **2.3** times larger than with PMTs
Stochastic term improved from
13.9%/√E up to **10%/√E**



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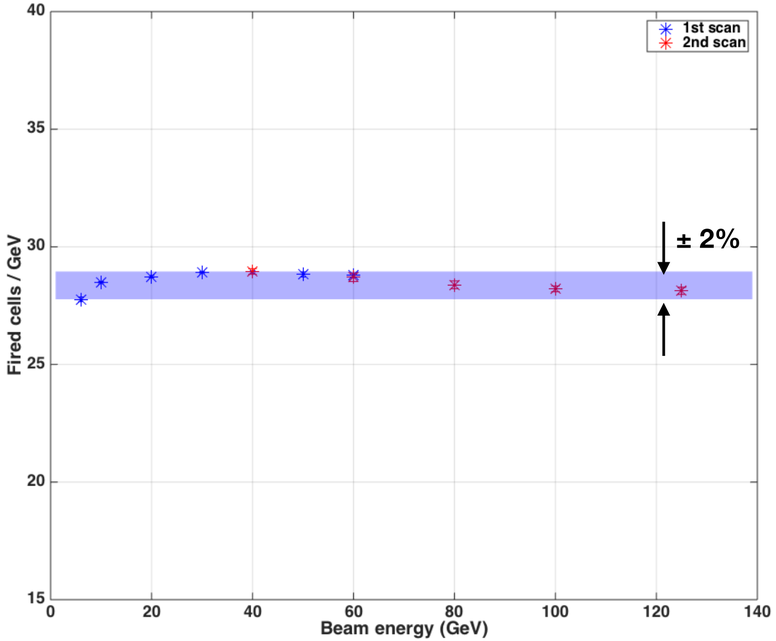
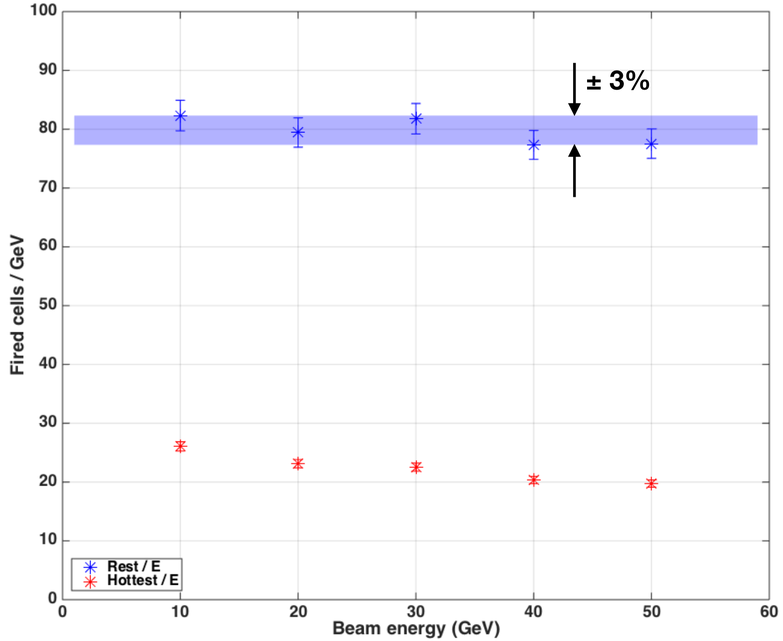


Scintillation signal

- V_{op} = **0.5 V_{ov}** (52.5 V) → **PDE ~ 2% to avoid saturation effects**
- **Correcting for non-linearity response** (first approximation)
- Correcting for the containment (45%) **3200 ± 200 fired cells/GeV**

The S signal is ~ **50** times
larger than the C signal

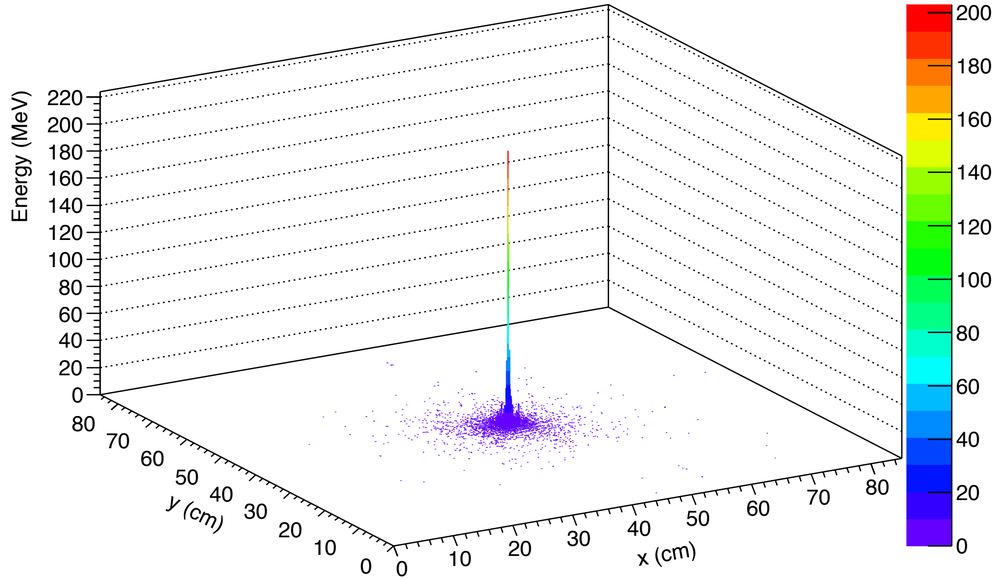


Results: spatial resolution

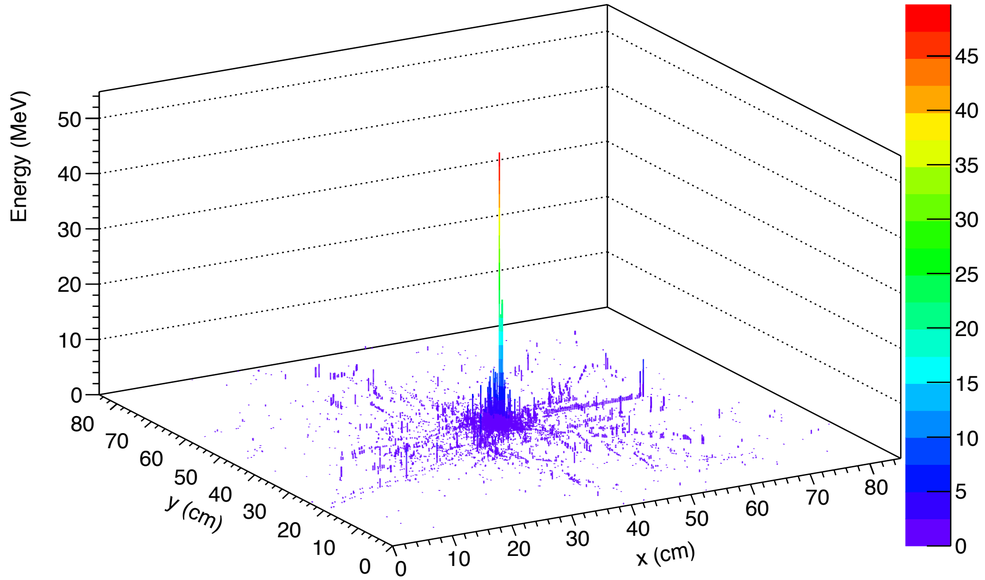
- The possibility of separately reading each fibre allows:
  - to sample em showers with a **millimeter spatial resolution**

Simulated energy deposition in scintillating fibres from 50 GeV

Electrons (e-)

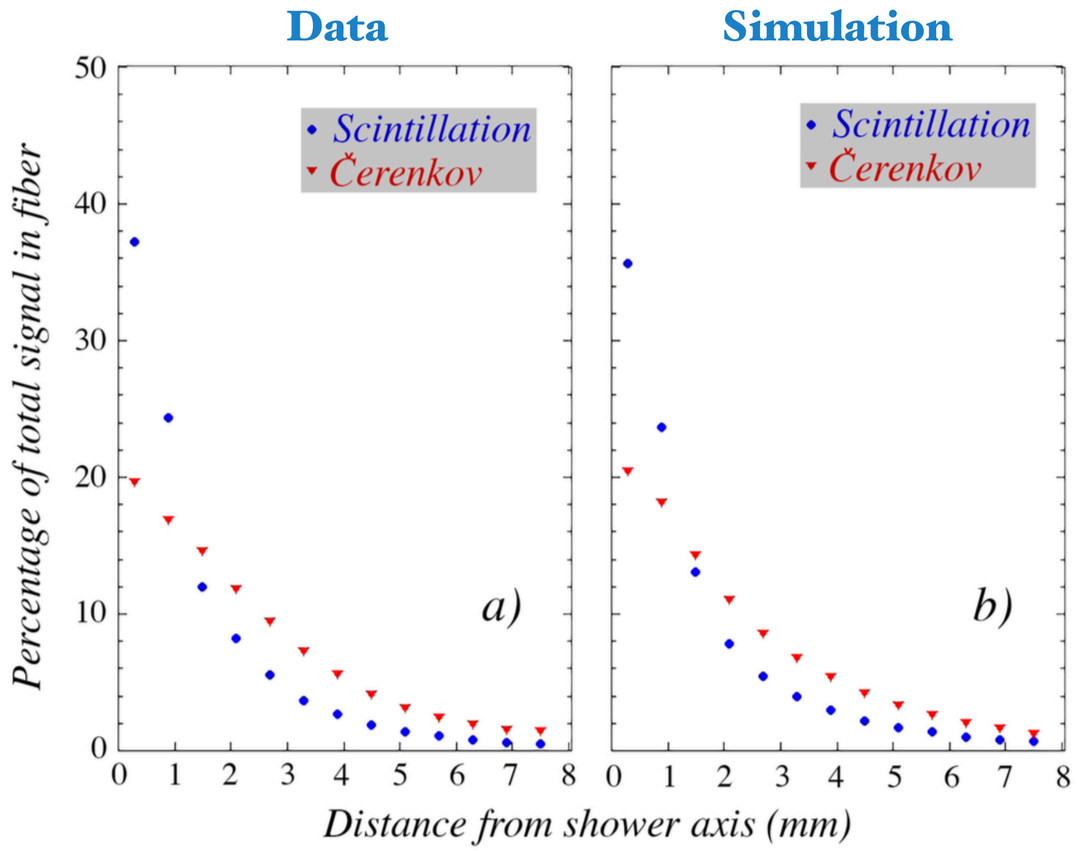


Pions (π-)



Results: lateral shower profiles

- The possibility of separately reading each fibre allows:
  - to sample em showers with a **millimeter spatial resolution**
  - to measure the **lateral profiles** very close to the shower axis



For each selected event:

- find the shower axis (using CoG):

$$\bar{x} = \frac{\sum_i x_i E_i}{\sum_i E_i}, \quad \bar{y} = \frac{\sum_i y_i E_i}{\sum_i E_i}$$

- find distance of each fibre to the shower axis:

$$r = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2}$$

- bin data (0.6 mm pitch) and find average

Results: lateral shower profiles

- The possibility of separately reading each fibre allows:
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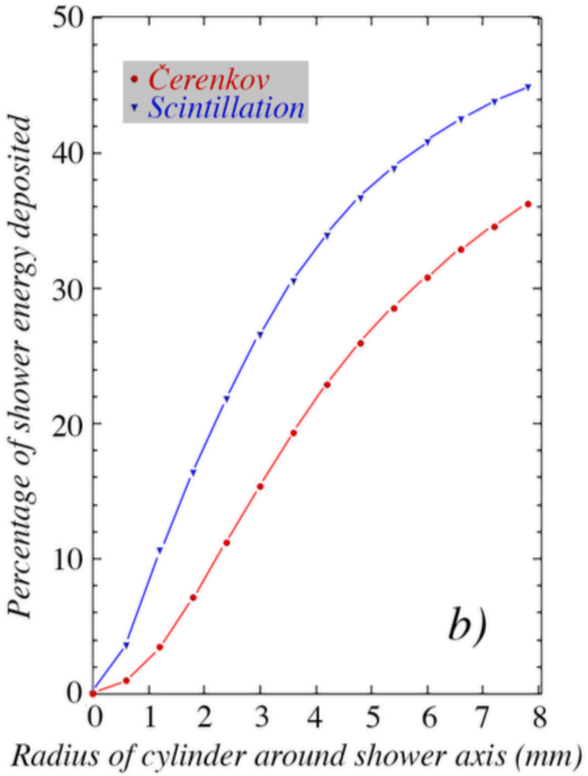
  - to measure the **lateral profiles** very close to the shower axis

Cumulative



For each selected event:

- find the shower axis (using CoG):

$$\bar{x} = \frac{\sum_i x_i E_i}{\sum_i E_i}, \quad \bar{y} = \frac{\sum_i y_i E_i}{\sum_i E_i}$$

- find distance of each fibre to the shower axis:

$$r = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2}$$

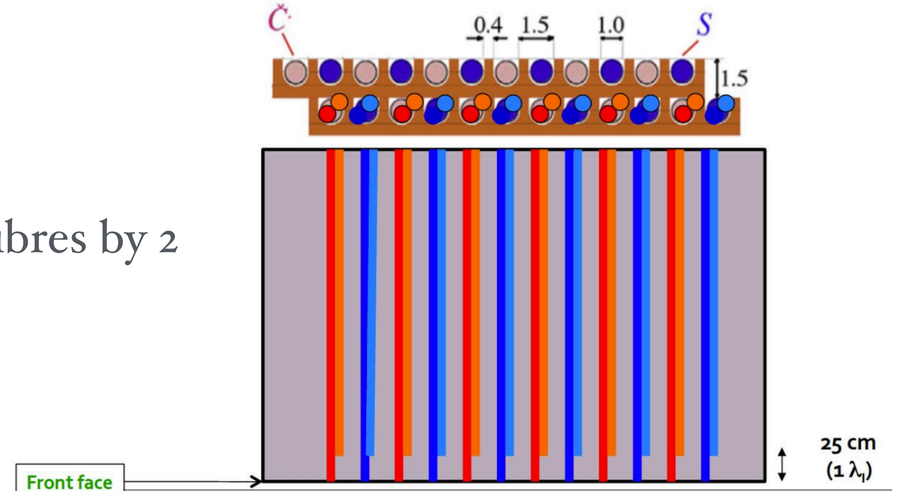
- bin data (0.6 mm pitch) and find average

About **half** of the energy is deposited within **few mm** from the shower axis and ~ **10% within 1 mm**

Results: longitudinal segmentation

- The possibility of separately reading each fibre allows:
  - to sample em showers with a **millimeter spatial resolution**
  - to measure the **lateral profiles** very close to the shower axis
  - to enable a possible **longitudinal segmentation**

- **Particle ID** in multi-particle environment has never been studied
- Possible ways to deal with it:
  1. **Put fibres starting at different depths:**
     - Keep the one-compartment design but multiply the number of fibres by 2
     - The additional fibres are **shorter by 1 λ_I**
  2. **Measure time properties of detecting photons:**
     - ToT, PkT, Ti, Tf ?
     - A real-time (feature-extracting) processor?



Next steps

Short term (2018 test beam):

- For the **IDEA** Vertical Slice:
  - Understand the **effect** of a **preshower** on the calorimeter performance
  - Test an RD52 (lead) module with the **dual-length fibre** option
- For the **SIPM**-based module:
  - **Reduce optical crosstalk** ⇒ improve fibre **insulation**
  - **Prevent the saturation** for S light ⇒ apply a **filter** and improve **dynamic range**
  - **Increase the cherenkov LY** ⇒ use an **aluminized glass mirror**
  - Test channel **grouping**/adding (1, 2, 4, 6, 9 channels summed up)

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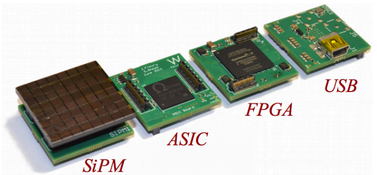


Middle and Long term (3-year R&D):

- Increase the SiPM module dimensions for a **full electromagnetic shower containment**
- Find an optimal readout electronics solution (**ASIC**, FPGA, etc)
- Investigate **machining** aspects and a scalable solution for a **4π geometry**
- **Geant4 full simulation:** study the impact of different **absorber materials** on the calorimeter performance, assess **particle ID capabilities** in multi-particle environment, investigate the main **physics channels** (i.e. detection of 2 jets and 2 tau's final states from H,W and Z)

All the publications used can be found at:

http://www.phys.ttu.edu/~dream/index.html

Please join us also at the

Poster Session

Backup Slides

More About Simulations

- The **em response** is simulated using a **30 x 30 x 100 cm³ copper** matrix, with 1 mm fibres and 1.5 mm distances.
  - The **constant term** is due to the S channel since this signal depends on the **impact point** for particles entering parallel to the fibres → this term can be avoided with a **small tilt** of the fibre axis
  - In the C channel the problem does not show up since the early component of the shower produce photons outside the numerical fibre aperture

- For the **hadronic response** is used a **80 x 80 x 250 cm³ copper** matrix, to obtain a containment of ~ 99%
  - Calibration was done with 40 GeV electrons beams

- In the **lead module** the limited lateral size of the matrix (~ 1λ) was allowing to collect, in average, only the **90%** of the shower energy, so that leakage fluctuations were dominating the resolution capability
- The resolution was also affected by the finite **light attenuation length** of fibres, causing early starting showers to be observed at lower signal values

Copper vs Lead

- Their main properties:
  - **Copper:** ρ = **11.3 g/cm³, X_0 = 0.56 cm, R_M = 1.60 cm, λ_{int} = 15.1 cm**
  - **Lead:** ρ = **8.96 g/cm³, X_0 = 1.44 cm, R_M = 1.56 cm, λ_{int} = 17.0 cm**

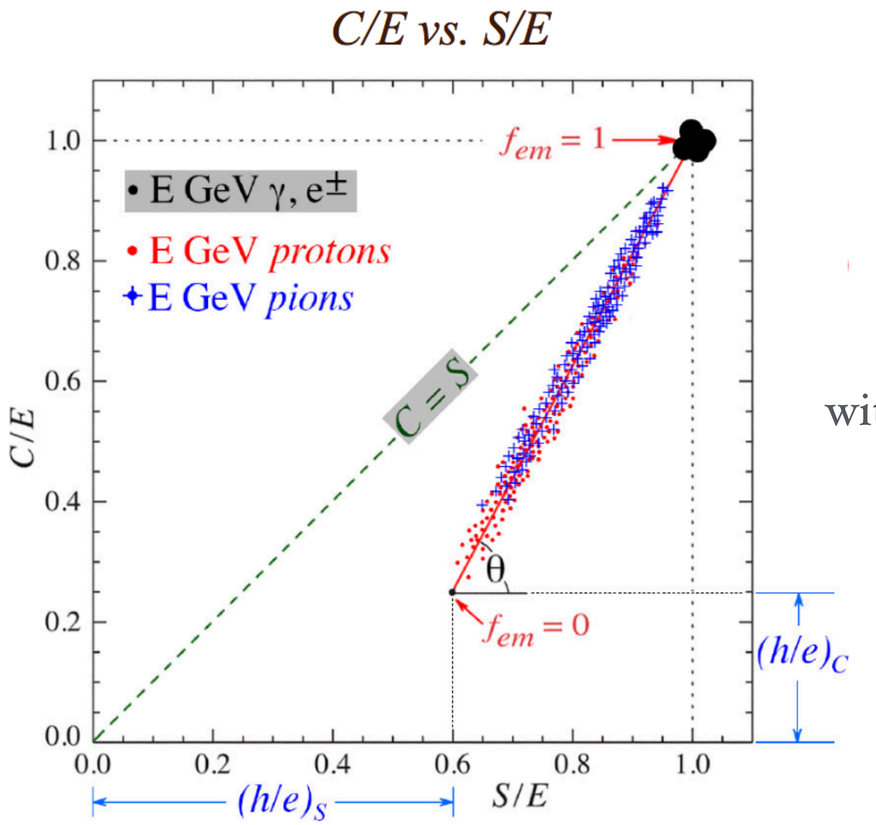
- This means that for hadronic showers, a full coverage solution with **lead will give broader and longer showers** and a total mass 42% heavier **than copper**.
- Being the C light almost exclusively produced by em component and the **e/mip** ratio **50% higher for copper** than for lead, the C LY should be higher in copper, resulting in a better hadronic resolution.
- But copper extrusion with the required tolerances in planarity and groove parallelism is not yet an established industrial processes.

- Alternative copper alloys (brass, bronze) will be investigated as well.

Dual-Readout Calorimetry

- Hadronic data points (S,C) located around straight lines

The plot shows that the data points are located on a locus, clustered around a line that intersects the C/S =1 line at the nominal beam energy



$$E = \frac{S - \chi C}{1 - \chi}$$

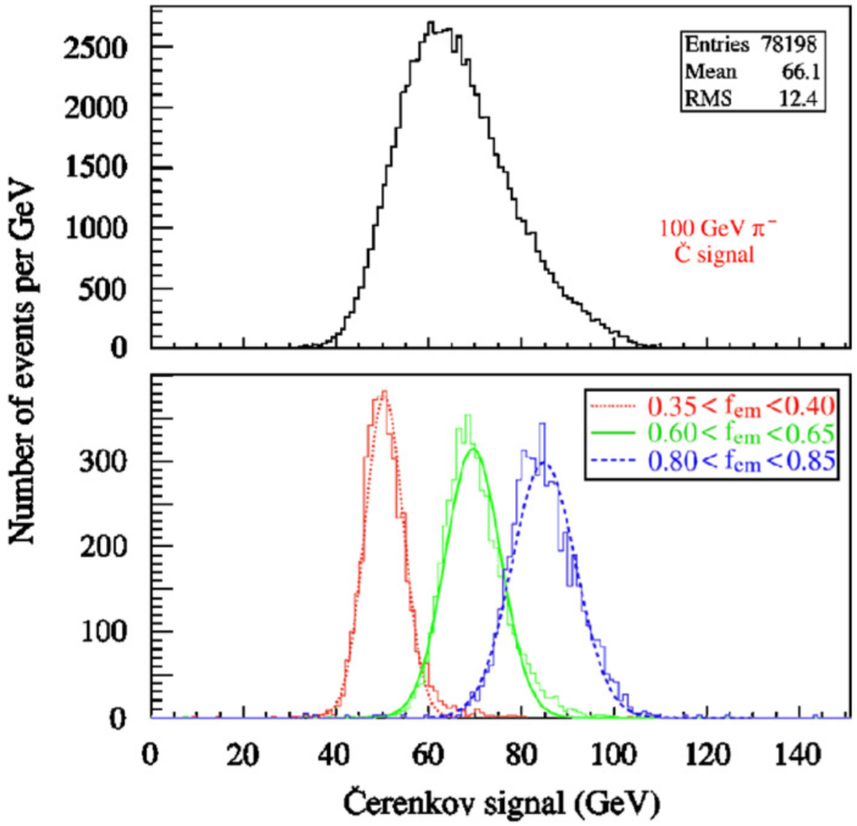
Universally valid!

with: $$\chi = \frac{1-(h/e)_S}{1-(h/e)_C} = \cot g(\theta)$$

χ is independent of both:

- Energy
- Type of hadron

Dual-Readout at Work

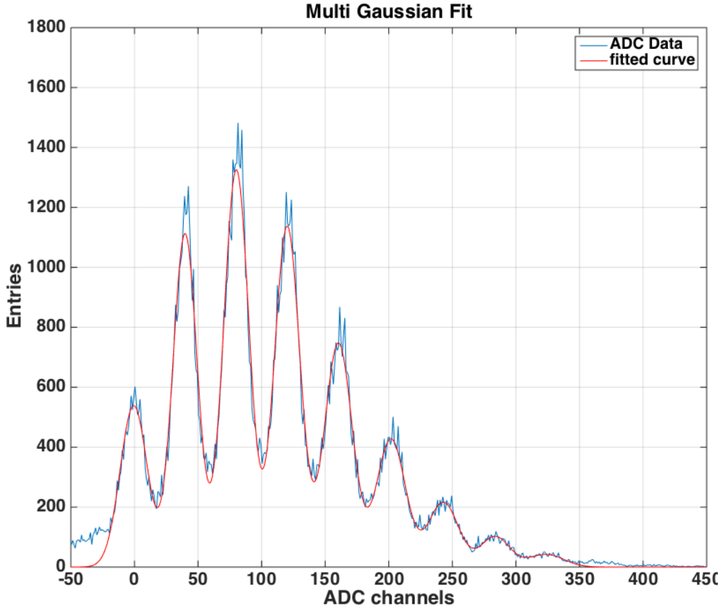


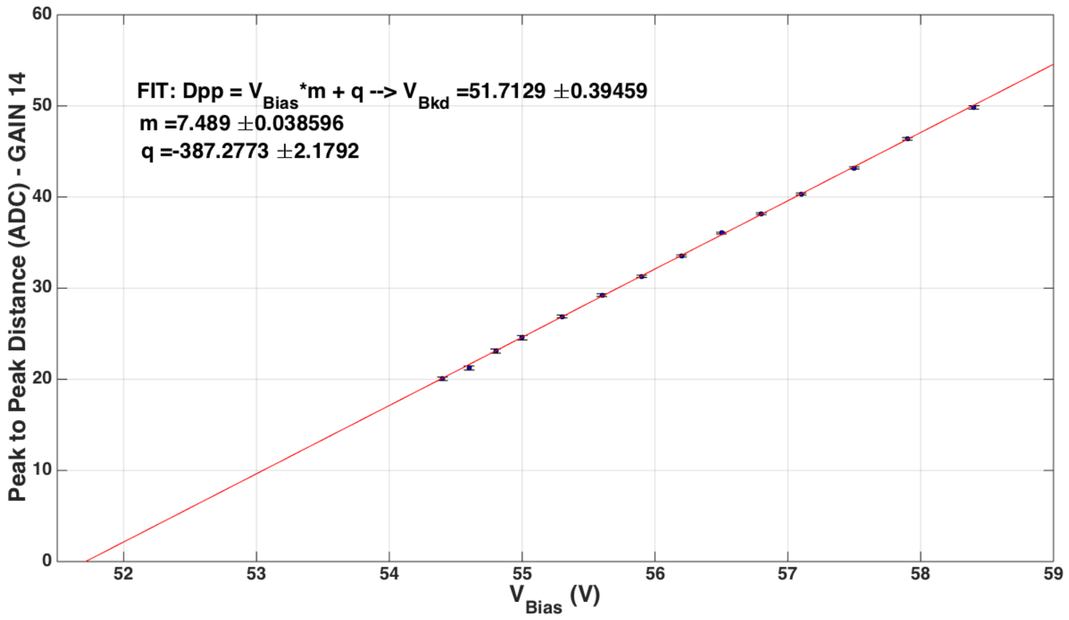
An example of the improvement that can be expected in the measurement of a sample of **100 GeV π's** if $f_{e.m.}$ is NOT measured (top plot) or if $f_{e.m.}$ bins are singled out

SiPMs

Calibration

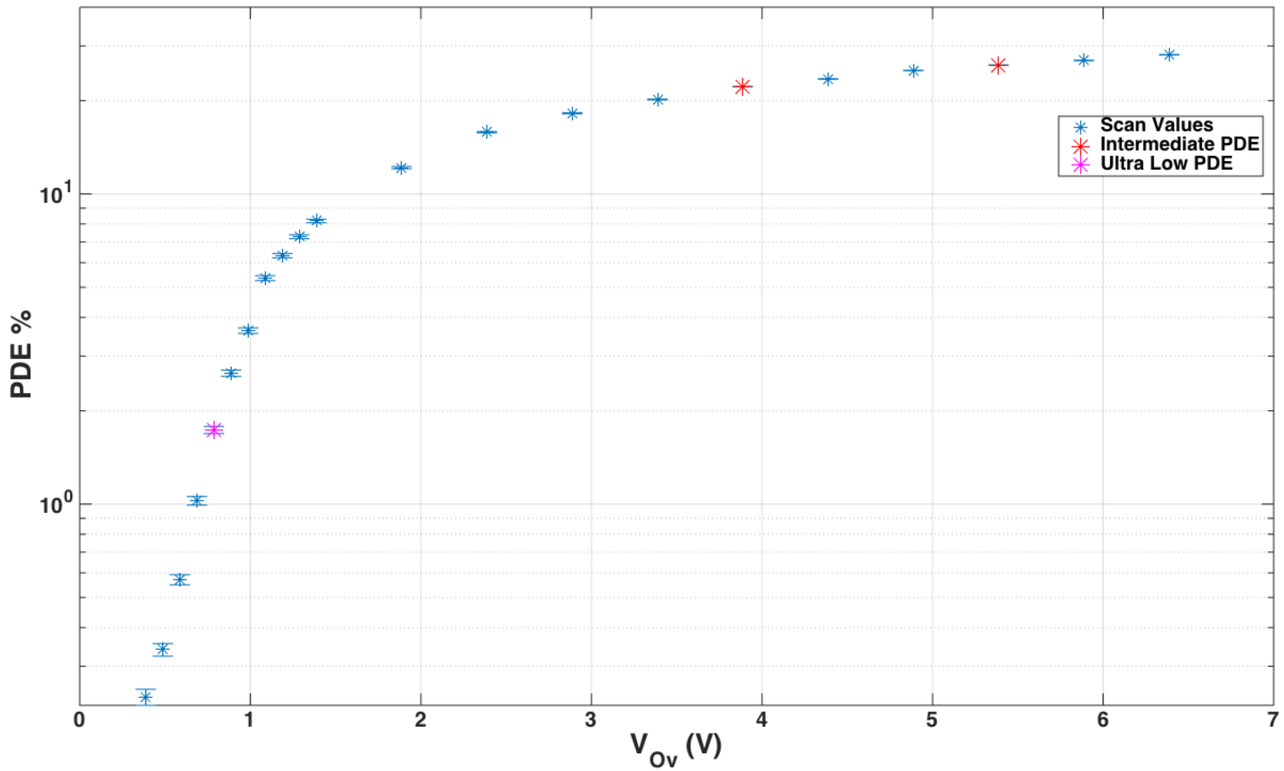
- Calibration done at 21.5 °C:
  - Same light conditions (**few** photoelectrons) at different V_{Bias}
  - **Peak to Peak** measured using the Multi Gaussian Fit
- Linear fit used to:
  - to extrapolate the Peak to Peak distance at low V_{Bias} (where the peaks are no longer distinguishable)
  - to measure the **V_{Bk} = 51.71 ± 0.39 V** (error < 1%)





PDE Measurements

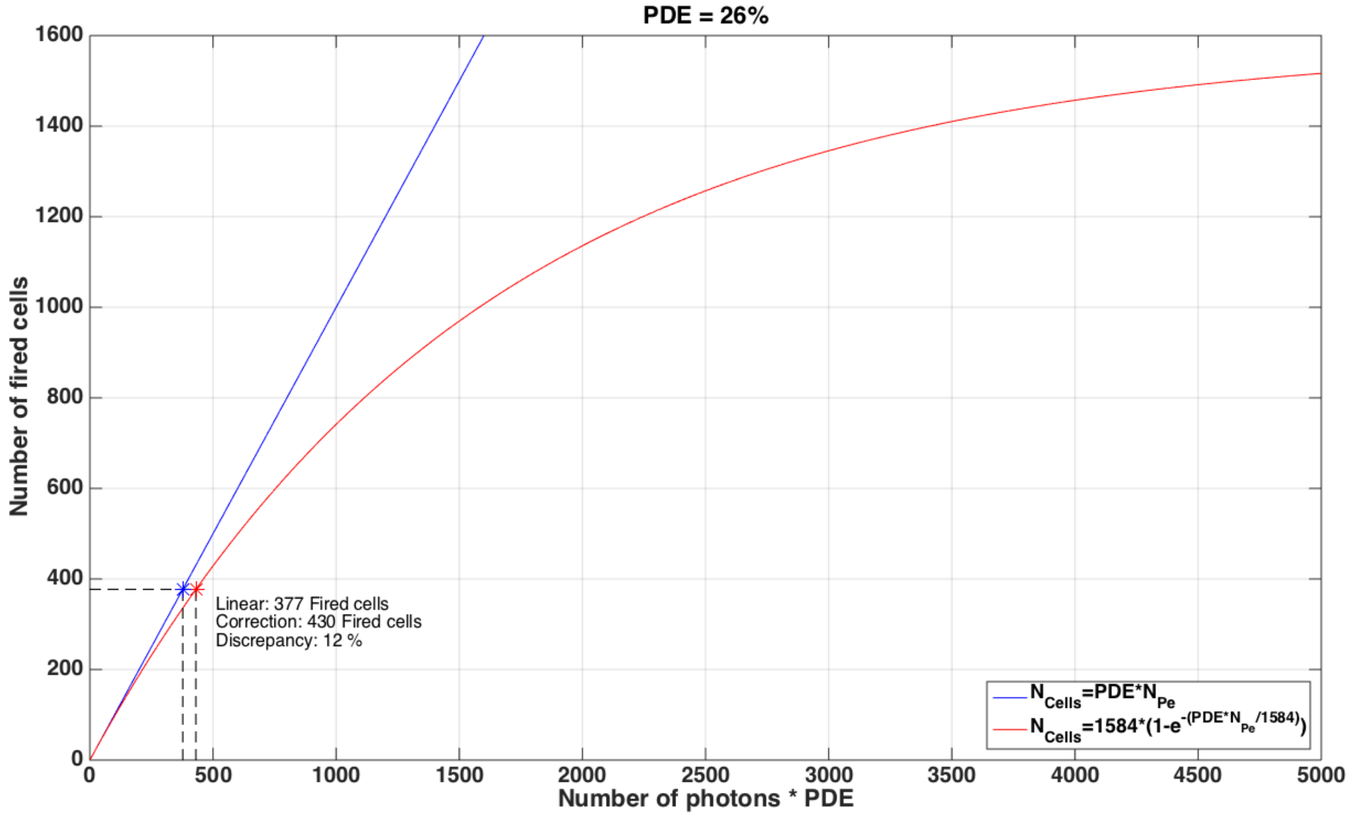
- **Relative PDE** measurement at different V_{Bias}:
  - Same amount of light for all measurements (24% of occupancy at nominal V_{Bias})
  - Number of fired cells extrapolated using the calibration
  - Relative PDE calculated —> absolute PDE reference point: **25% at + 5 V_{Ov}** @ 25 °C



Non-Linearity Correction

- Correction applied:

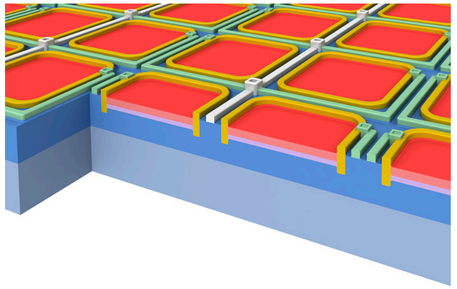
$$N_{fired} = 1584\left(1 - e^{\frac{-\#Photons*PDE}{1584}}\right)$$

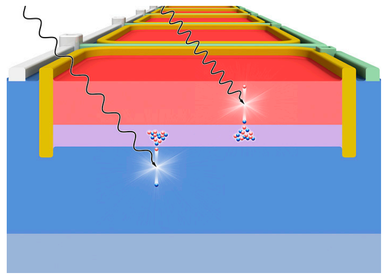


SiPM: Silicon Photomultipliers

Principles

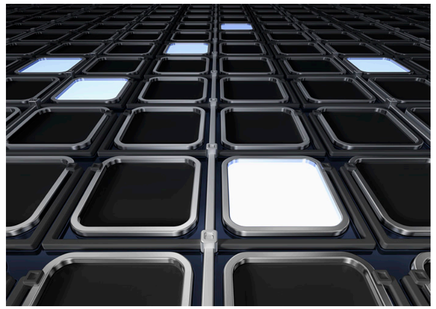
SiPM = High density (~10^4/mm^2) matrix of diodes with a common output, reverse biased, working in Geiger-Müller regime



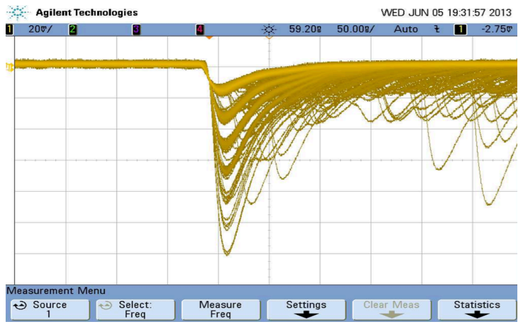


When a photon hits a cell, the generated charge carrier triggers an avalanche multiplication in the junction by impact ionization, with gain at the 10^6 level

Operation



- SiPM may be seen as a collection of binary cells, fired when a photon in absorbed
- "counting" cells provides an information about the intensity of the incoming light:



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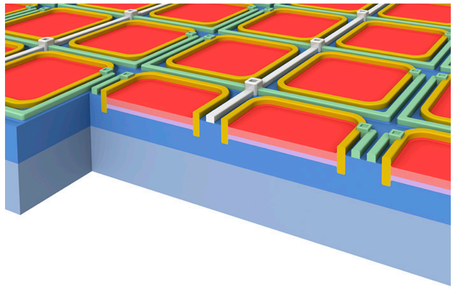

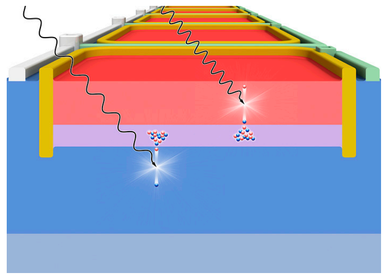

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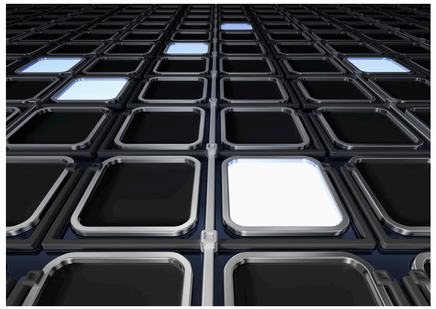

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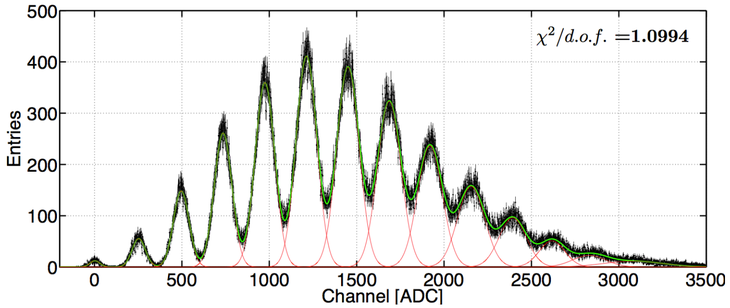
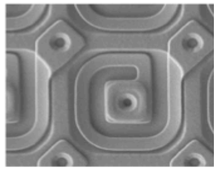


SiPM: Silicon Photomultipliers

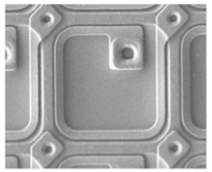
- It's possible to choose the "best fit" device for each application:

in terms of pixel pitch:

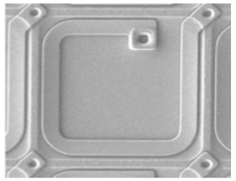
10 μm



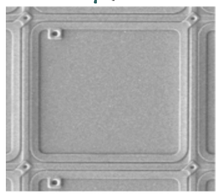
15 μm



25 μm



50 μm



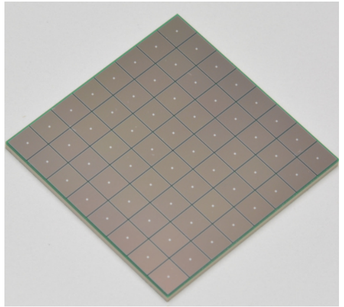
75 & 100 μm are available as well

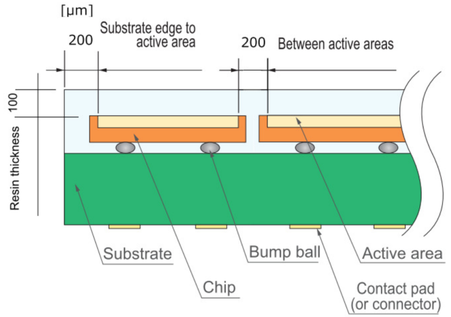
Not to mention the variety of available options for the front-end, the packaging and the near future integration with the read-out electronics

in terms of sensor area:

- 1x1 mm²
- 3x3 mm²
- 6x6 mm²

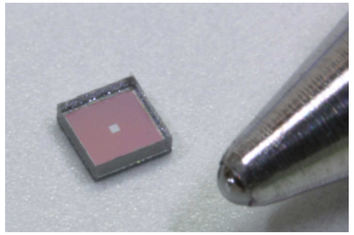
- 1x4 mm²
- 12x12 mm²
- 24x24 mm²

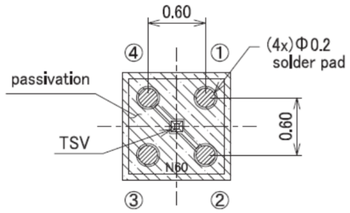


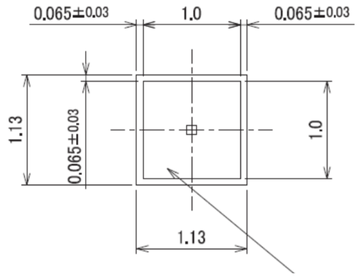


SiPM: Silicon Photomultipliers

- Recently, thanks to the Through Silicon Via (TSV) technology, HAMAMATSU offered **arrays built up on a mosaic of 1 x 1 mm² sensors**, quite appealing for the envisaged application:





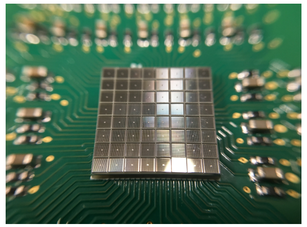


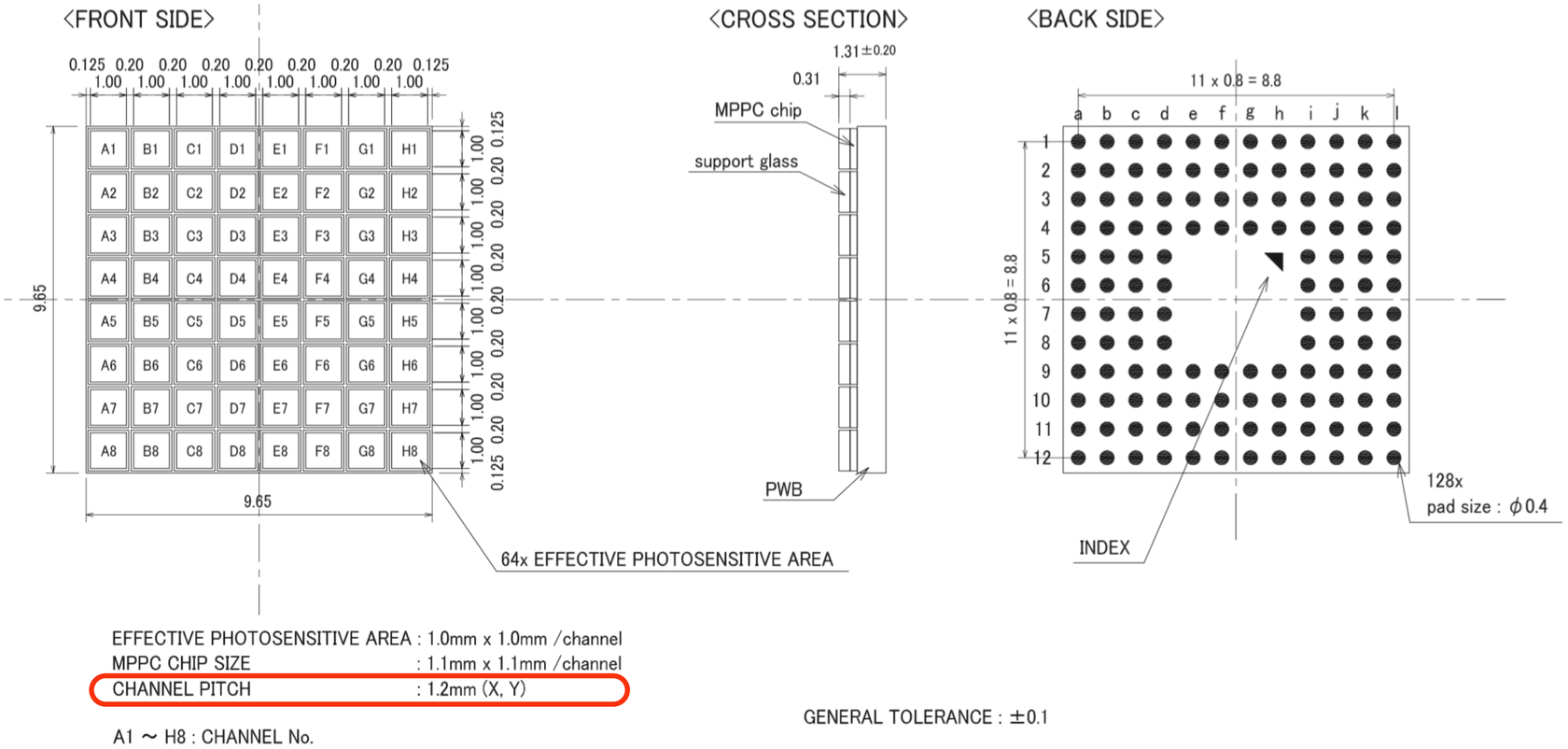
Parameters	S13615 -1025	S13615 -1050	Unit
Effective photosensitive area	1.0x1.0		mm^2
Pixel pitch	25	50	μm
Number of pixels / channel	1584	396	-
Geometrical fill factor	47	74	%

Parameters		Symbol	S13615 -1025	S13615 -1050	Unit
Spectral response range		λ	320 to 900		nm
Peak sensitivity wavelength		λp	450		nm
Photon detection efficiency at λp*3		PDE	25	40	%
Breakdown voltage		V_{BR}	53 ±5		V
Recommended operating voltage*4		V_{op}	V_{BR} + 5	V_{BR} + 3	V
Dark Count	Typ.	-	50		kcps
	Max.		150		
Crosstalk probability	Typ.	-	1	3	%
Terminal capacitance		Ct	40		pF
Gain*5		M	$7.0x10^5$	$1.7x10^6$	-

SiPM: 8x8 Matrix

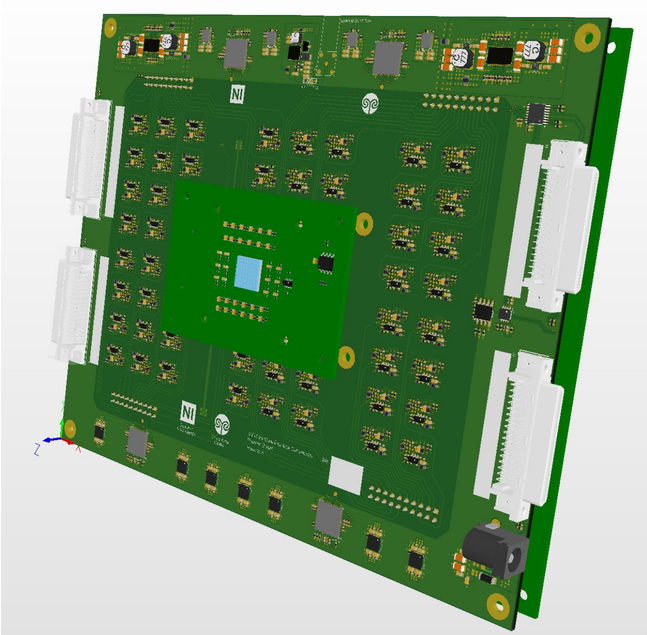
- The development was based on **8x8 channel arrays** and we have got in September 2016 the first samples ever produced (serial no. 1 & 2) with both **25 µm** and **50 µm pitch** [the latter only was used in the test beam]

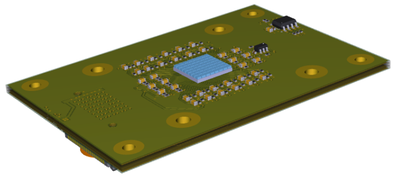


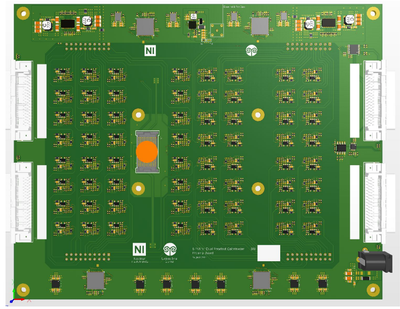


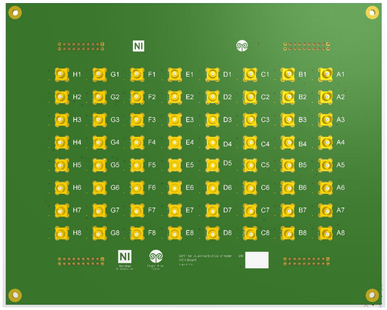
Sensor Boards

The sensor system









1. **the daughter board**
   providing an independent bias to the 64 sensors and integrating T measurement for gain compensation

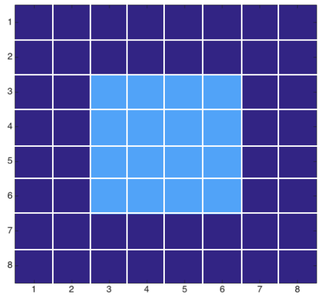
2. **the mother board**
   - amplifying & shaping the output of each sensor
   - routing the signals to the digitization system

3. **the backplane board**
   allowing to probe via mcx connectors each channel

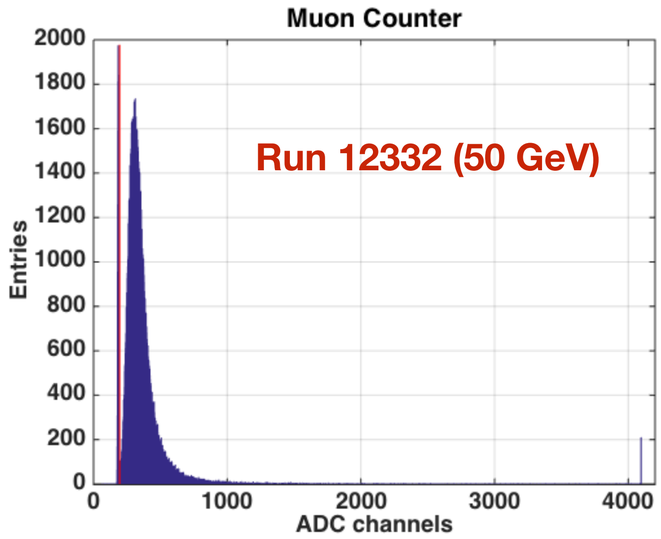
Beam Test

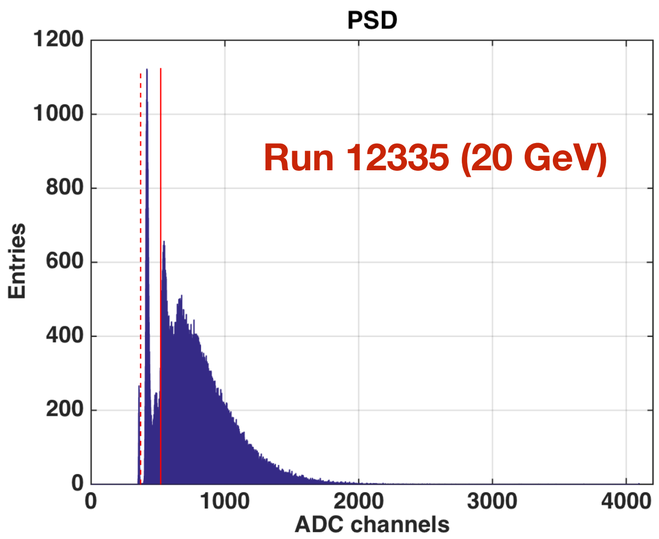
Cut for E- Selection

- **Geometrical cut:** events with the maximum signal in the central box **(4x4)**



- **Noise cut:** events with the total number of fired cells (sum on all SiPM signals) greater than **20** ph.e.
- **Muons cut:** events with a signal in the muon counter below threshold
- **PSD cut:** events with a signal in the PSD above threshold





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